PILE LAYOUT TO MINIMIZE INTERFERENCE

EXAMPLE 1
PILE LENGTH, SPACING, AND DIAMETER OPTIONS
PILE IN UNIFORM CLAY

1. Description

This example illustrates the evaluation of design alternatives for a pile group in a uniform clay. Eight alternative designs are developed and the probability of intersection, expected number of intersections, and comparative costs and risks of intersection are determined for each design.

2. Design Requirements and Static Analysis

Assume a group of steel pipe piles are to be driven in a uniform clay. The piles are to support a load of 7 kips/sq ft over a 20-ft square area and provide a factor of safety of 2.5. Thus, the required ultimate capacity of the group is 7.00 × 20 × 20 × 2.5 = 7,000 kips. The static pile capacity is to be determined by the α method (EM 1110-2-1906). The undrained strength (or cohesion), s_u of the clay is 1,000 lb/sq ft and the skin resistance, f ($f = \alpha s_u$), is 750 lb/sq ft.

The ultimate pile capacity for a single pile, Q_{ult}, is:

$$Q_{ult} = Q_{side} + Q_{tip}$$

$$Q_{ult} = fpL + 9 s_u A_{tip}$$

Where

Q_{side} is the ultimate side or shaft resistance
Q_{tip} is the ultimate tip or point resistance
p is the perimeter of the pile
L is the embedded length of the pile
A_{tip} is the cross-sectional area of the pile tip

The capacity of the group is the lesser of the capacity of a single pile times the number of piles,

$$Q_{group} = nQ_{ult}$$

or the capacity of the entire group failing as a unit:

$$Q_{group} = p_{group} L_{group} \alpha s_u + N_c s_u A_{group}$$

where

n is the number of piles in the group
p_{group} is the perimeter of the group
L_{group} is the pile length, or embedded depth of the group
N_c is a bearing capacity factor between 5.14 and 9, depending on the width to depth ratio of the group
A_{group} is the base area of the group

It is assumed that piles can be spaced on 4- or 5-ft centers; thus, the group can consist of 25 piles spaced on 5-ft centers as shown in Figure 4-1 or

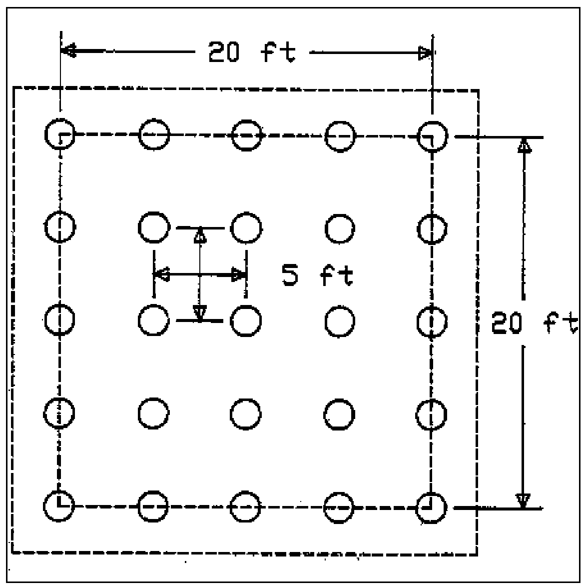

Figure 4-1. Twenty-five piles on 5-ft centers

36 piles spaced on 4-ft centers as shown in Figure 4-2. It is further assumed that piles of 12, 14, 16 and 18 in. diameters can be used. By calculating the required pile length to provide 7,000 kips ultimate capacity, eight comparative pile designs were developed using a microcomputer spreadsheet; an example printout from the spreadsheet is shown

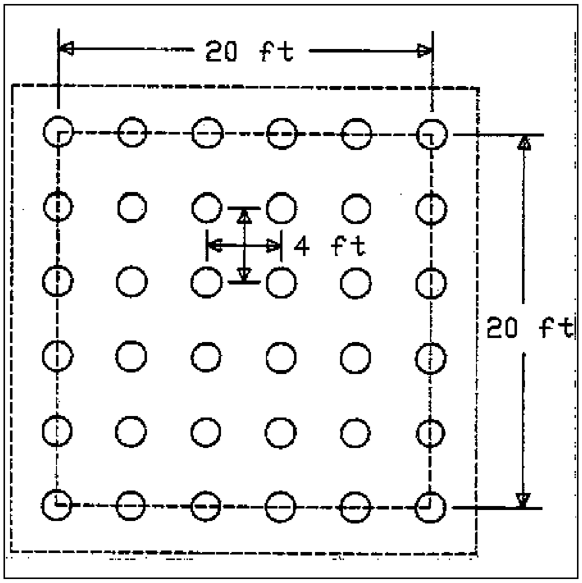

Figure 4-2. Thirty-six piles on 4-ft centers

in Figure 4-3. The resulting designs are tabulated below:

A: 36 piles, 4 ft spacing, 12 in. diameter, 80 ft long, Q_{ult} = 7,040 kips
B: 36 piles, 4 ft spacing, 14 in. diameter, 70 ft long, Q_{ult} = 7,274 kips
C: 36 piles, 4 ft spacing, 16 in. diameter, 60 ft long, Q_{ult} = 7,238 kips
D: 36 piles, 4 ft spacing, 18 in. diameter, 55 ft long, Q_{ult} = 7,570 kips
E: 25 piles, 5 ft spacing, 12 in. diameter, 120 ft long, Q_{ult} = 7,245 kips
F: 25 piles, 5 ft spacing, 14 in. diameter, 100 ft long, Q_{ult} = 7,113 kips
G: 25 piles, 5 ft spacing, 16 in. diameter, 90 ft long, Q_{ult} = 7,383 kips
H: 25 piles, 5 ft spacing, 18 in. diameter, 75 ft long, Q_{ult} = 7,024 kips

Each of the designs A through H will provide an ultimate capacity of just over 7,000 kips; however, each will have a different settlement, a different probability of intersection, a different cost, and a different financial risk attributable to possible intersection. The settlement calculations are beyond the scope of this example; however, everything else being equal, the designs with the greatest pile lengths (and hence the smaller diameter piles) will have the least settlement. Probability of intersection and cost considerations are discussed in the next section.

3. Probability of Intersection

From the published chart solutions, the probabilities of intersection for individual piles were determined for each of the eight designs. Using these probabilities and the group layouts, the probability distribution on the number of intersections was determined using the software package CPGP. The results are shown in Table 4-1.

The probability that one or more intersections will occur varies from about 10 percent for design A to about one-half of 1 percent for design H, or a twentyfold difference. The lowest probability of intersection occurs for the greater pile spacing, largest diameter pile, and a relatively short pile length.

4. Financial Risk

Consideration of the expected cost of possible intersections may provide a quantitative perspective to aid in making design decisions. Representative unit cost data for this example were provided by the Cost Engineering Section of the St. Louis District. Material costs were assumed to vary from $20.00/ft for 12-in. piles to $29.00/ft for 18-in. piles. Equipment and labor was taken at $530/hr. A set of productivity curves was provided giving the number of piles driven per hour as a function of pile length and diameter. Using these data, the comparative costs were determined assuming no intersections occur (Table 4-2).

For this example, the cost of an intersection is taken to be an additional cost equal to twice the furnishing and driving cost times two piles, as the piles must be both pulled and redriven, requiring two additional setups. There may be significant additional delay costs; these are assumed to be a flat $2,000.00 per intersection for the purpose of this example. The financial risk due to the possibility of intersection is the expected number of

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|   A   ||   B   ||   C   ||   D   ||   E   ||   F   ||   G   ||   H   |
Pile Capacity for Friction Pile in Uniform Clay
T.F. Wolff and T.J. Mixter, 19 July 1990


Undrained Strength on Side,     su =  1000.00      psf
adhesion factor,             alpha =      .75
skin friction,                   f =   750.00      psf

Undrained Strength at Tip       su =  1000.00      psf
Tip Bearing                9 * su =   9000.00      psf


                      12 in    14 in    16 in    18 in
    L, ft           Q, kips  Q, kips  Q, kips  Q, kips
------------------------------------------------------------------------
    50.00            124.88   147.07   169.65   192.62
    60.00            148.44   174.55   201.06   227.96
    70.00            172.00   202.04   232.48   263.30
    80.00            195.56   229.53   263.89   298.65
    90.00            219.13   257.02   295.31   333.99
   100.00            242.69   284.51   326.73   369.33
   110.00            266.25   312.00   358.14   404.68
   120.00            289.81   339.49   389.56   440.02


CALCULATING THE GROUP EFFICIENCY OF PILES
GIVEN A GROUP OF PILES DIMENSIONED n1 X n2
IN AN AREA Bg X Lg

     n1 =        6                           <----- Lg ----->
     n2 =        6                      /\   o    o    o    o
     Bg =    21.00 (feet)                |                        /\
     Lg =    21.00 (feet)               Bg   o    o    o    o   |
      d =       12 (inches)              |                        n1
      c =     1000 (psf)                \/   o    o    o    o   _
      D =    80.00 (feet)
  alpha =      .75                           | n2 --->
spacing =     4.00

The group capacity is the lesser of the following two equations:

Equation 1:

   Capacity = n1 * n2 * ( Qt + Qs ) = N * ( Qt + Qs )

         where Qt = At * ( 9 * c )
               Qs = ( fs * As )

                  where fs = Ca = alpha * c
                        As = area of pile in contact with soil

   Capacity =          7040 (kips)


Equation 2:

   Capacity = 2 * ( Bg + Lg ) * D * Cav
              + [5 * (1 + D/ 5/ Bg) * (1 + Bg/ 5/ Lg)] * Cb * Lg * Bg
                  where Cav = alpha * c
                  Nc(calc)= 5 * ( 1 + D / 5 /Bg) * ( 1 + Bg / 5 / Lg )
                  Nc(calc)=    10.57          (maximum = 9)
                       Nc =        9

   Capacity =          9009 (kips)

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Figure 4-3. Example of spreadsheet calculation of group capacity

Table 4-1
Probability Distribution

Design	Spacing ft	Diameter in.	L ft	Pr[I] (pile)	E[I] (group)	Pr[I =0] (group)	Pr[I >0] (group)
A	4	12	80	.004	.1	.9048	.0952
B	4	14	70	.002	.05	.9512	.0488
C	4	16	60	.0006	.015	.9851	.0149
D	4	18	55	.0008	.02	.9802	.0198
E	5	12	120	.005	.08	.9231	.0769
F	5	14	100	.003	.048	.9531	.0469
G	5	16	90	.0015	.024	.9763	.0237
H	5	18	75	.0003	.0048	.9952	.0048

Table 4-2
Comparative Costs

Design	Number of Piles	Pile Diam. in.	Pile Length ft	Driving Time piles/hr	Driving Costs $/ft	Material Costs $/ft	Total Unit Cost $/ft	Total Cost $
A	36	12	80	1.00	$ 6.63	$ 20.00	$ 26.63	$ 76,680
B	36	14	70	1.11	$ 6.82	$ 23.00	$ 29.82	$ 75,149
C	36	16	60	1.25	$ 7.07	$ 25.00	$ 32.07	$ 69,264
D	36	18	55	1.03	$ 9.36	$ 29.00	$ 38.36	$ 75,957
E	25	12	120	.66	$ 6.68	$ 20.00	$ 26.68	$ 80,041
F	25	14	100	.72	$ 7.36	$ 23.00	$ 30.36	$ 75,910
G	25	16	90	.69	$ 8.53	$ 25.00	$ 33.53	$ 75,441
H	25	18	75	.60	$ 11.73	$ 29.00	$ 40.73	$ 76,365

intersections times the cost of an intersection. The total expected costs of the alternative designs are thus:

Base cost + E[I] x (4 x L x $/ft + delay cost)

Design A $76,680 + 0.1000 x (4 x 80 x $26.63/ft + $2,000) = $77,732
Design B $75,149 + 0.0500 x (4 x 70 x $29.82/ft + $2,000) = $75,666
Design C $69,264 + 0.0150 x (4 x 60 x $32.07/ft + $2,000) = $69,409
Design D $75,957 + 0.0200 x (4 x 55 x $38.36/ft + $2,000) = $76,166
Design E $80,041 + 0.0800 x (4 x 120 x $26.68/ft + $2,000) = $81,226
Design F $75,910 + 0.0480 x (4 x 100 x $30.36/ft + $2,000) = $76,588
Design G $75,441 + 0.0015 x (4 x 90 x $33.53/ft + $2,000) = $75,462
Design H $76,365 + 0.0003 x (4 x 75 x $40.73/ft + $2,000) = $76,369

The resulting costs are plotted as a function of pile diameter in Figure 4-4. The solid curves are the total direct costs, and the dotted curves are the total expected costs including the expected cost due to interference. The two curves provide the designer a visual characterization of the financial risk of intersection. It is noted that the expected cost difference due to interference is greatest for the designs utilizing 12 in. piles, where the greatest pile lengths are

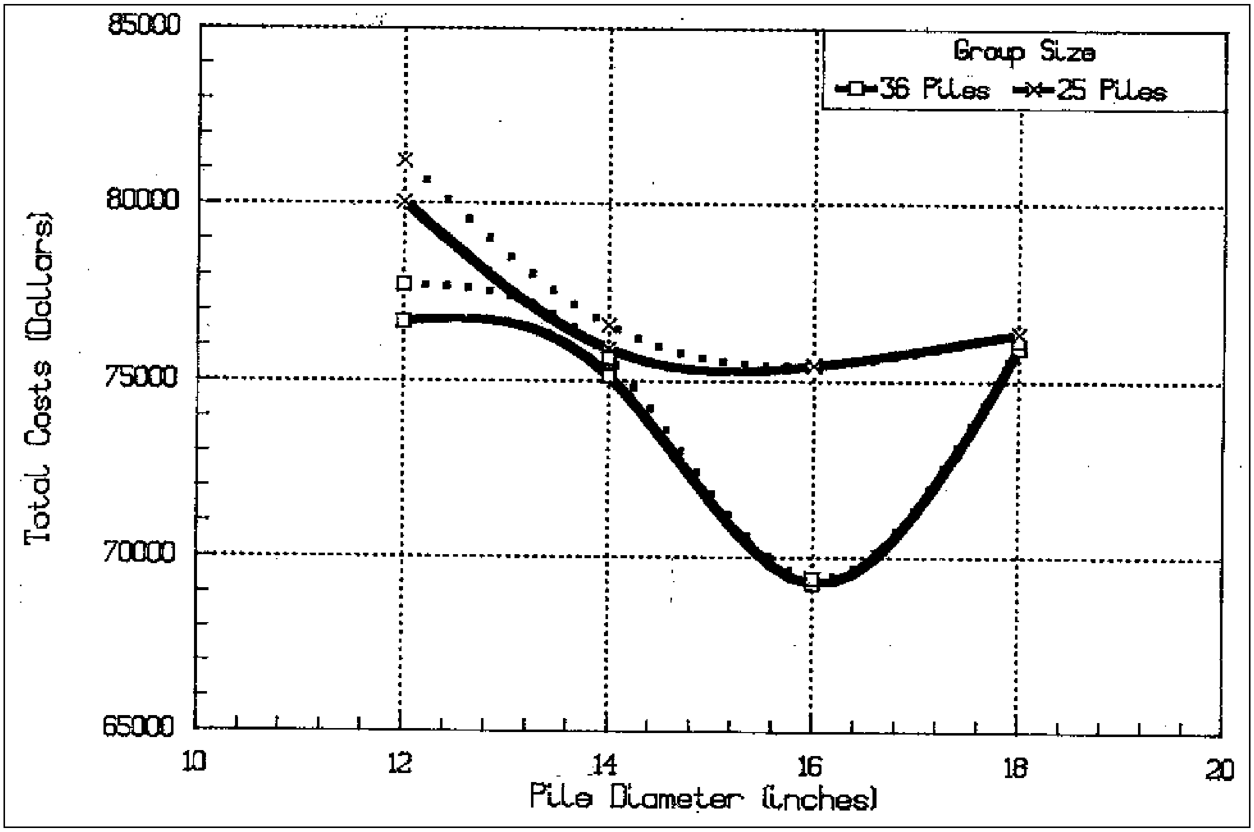

Figure 4-4. Comparative pile group costs

required, and are virtually negligible for the designs utilizing 18 in. piles, where the comparatively short pile lengths are associated with very small intersection probabilities. While the cost differences are not great in this particular example, they could differ greatly if the delay costs caused by intersection were higher.